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Design of Intelligent Control Systems for Layered Water Injections in Oilfields

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ABSTRACT

With rapid socio-economic growth and increased energy demand, exploration and exploitation of oil and gas resources have become crucial. Long-term exploitation leads to problems such as pressure drop and production reduction in oil fields, and water injection technology has become a common method to improve these problems. The traditional direct water injection for oil extraction has problems such as high injection cost and low oil recovery efficiency. Therefore, an intelligent control system for different oilfield reservoirs is needed. This study focuses on the layered water injection intelligent system based on advanced sensor technology, digital signal processing and intelligent algorithms. The article reviews the advantages of layered water injection system and the current research status, designs an intelligent control structure including hardware circuits and modular software processes, and adopts adaptive particle swarm optimization algorithm as the core of intelligent control.

KEYWORDS

Control System, Design, Layered Water Injection, Intelligent, Oil Recovery Engineering

INTRODUCTION

Oil and gas resources are currently one of China's most important primary energy concerns. Consequently, exploring oil resources, exploitation, and engineering applications related to national industrial development and national livelihood, as well as ensuring high-quality production of oil fields, is of great strategic significance. With the rapid development of society and sustained economic growth, people's demand for oil and gas resources is also increasing(Lei et al., 2023). After many years of exploitation, domestic oil reservoirs are decreasing. This decrease results in lower reservoir oil pressure, leading to increases of the oil-to-gas ratio, a rise in the viscosity of crude oil, and a reduction in the yield (Cheng et al., 2022).

Improvement of these problems through a water injection process has become a common means of oil recovery engineering. After years of development of water injection technology, a better system has emerged; however, longtime water injection oil extraction creates high water

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content in oil fields. Oil field reservoirs comprise several layers to dozens of layers that vary. The traditional direct injection of water into oil leads to the high cost of water injection, low oil recovery efficiency, and other issues. Therefore, an intelligent control system for automatic water injection for different oil field reservoirs is urgently needed(Su et al., 2021). For this paper, we researched technologies, such as advanced sensors and digital signal processing (DSP), as well as intelligent algorithms, and focused on the research of layered water injection intelligent systems. We summarized the advantages of a stratified water injection system, and the current research status of academia and industry at home and abroad provided us with the intelligent control structure of the stratified water injection researched for this paper. We focused on the research of water injection flow regulating valve and high-pressure seals, sensors, and other downhole actuators; hardware circuit designs that include peripheral information acquisition, output drive, communication, and other functions; and designs for modularized software flow based on TMS320F28335. We also researched modularized software flow based on adaptive particle swarm optimization (PSO) technology (Wang, 2022). We also focused on design of the modular software flow based on TMS320F28335, which provides the intelligent control core based on the adaptive PSO algorithm. Currently, the oil industry is moving toward the development of green oil fields and digital oil fields, as well as the combination of oil extraction engineering and digitization and information technology, to solve practical engineering problems; this movement is important for the future development of the oil industry (Yue et al., 2021).

In the second quarter of 2023, the International Energy Agency (IEA) and world-renowned energy consultancy Rystad Energy have released the Global Energy Progress Report and the Global Petroleum Resource Data Report. The IEA's Global Energy Progress Report compares the trends in the top 20 energy-consuming countries for the periods 2000-2010 and 2010-2019. Among the 20 countries with the largest total energy supply in the world, 13 countries have seen their energy intensity increase at an annual rate. However, less than half of the top energy-consuming countries are performing better than the global average. China continues to increase its energy intensity at the fastest rate, with a compound annual growth rate (CAGR) of 3.8% between 2010 and 2019, followed by the United Kingdom at 3.7%. Japan and Germany also continue to increase their energy intensity, exceeding the 7.3 target (Du, 2019). In a report by Norwegian Ruide, recoverable oil reserves are currently estimated at 1.572 trillion barrels globally. According to the Ministry of Natural Resources, PRC's 2021 China Mineral Resources Report, in 2020, China's oil, natural gas, and remaining proven technically recoverable reserves reached 3.619 billion tons, 626,657,800,000,000 cubic meters. China is a major oil consumer and importer from large countries. It imported 513 million tons of crude oil in 2021 and consumed about 707 million tons. China's own annual oil production is below 200 million tons, and China's oil imports are far more than its own extraction. The growth rate of China's imports is also higher than its growth rate of extraction. The exploitation of a large number of oil and gas fields has resulted in an increase in a large number of underground crude oil viscosity. Crude oil is difficult to flow smoothly, and in some cases, depletion occurs. This, combined with the lack of energy to drive the oil forward, makes it challenging to exploit effectively. In the face of the lack of repellent energy, water injection technology is usually used to maintain the pressure of each oil layer, thus improving the oil recovery efficiency and reducing the cost of crude oil production. Table 1 lists data for oil prospecting and production research by country.

Since the 1960s, when the first crude oil gushed out of Daqing Oil Field, China has been continuously developing and innovating in the field of crude oil extraction technology. After years of research and development, China has been in a leading position in the world in terms of oil extraction and the process of water injection. At present, the mainstream water injection technology used in the domestic and foreign oil industry is layered water injection technology, the principle of which is to use the packer. The packer starts with the first layer of the oil field and then completes layer-by-layer water distribution—that is, a small amount of water injection in a high permeability oil layer and a low permeability oil layer to strengthen the water injection (Wang et al., 2022). Compared

Table 1. World major oil prospecting and production research

Total number of detections			Yield		
Number	Country	Reserves (tons)	Number	Country	Reserves (tons)
1	Saudi Arabia	3,553,424	1	Saudi Arabia	42,150
2	Canada	2,450,589	2	Russia	41,080
3	Iran	1,723,287	3	America	28,625
4	Iraq	1,575,342	4	Iran	18,650
5	Kuwait	1,321,917	5	China	17,075

with the mixed water injection technology adopted in the early stage, the layered water injection will not have the problem of uneven water distribution in some well sections affecting the oil repellent effect, and it is more effective and reliable. With the long-term exploitation of oil and gas fields, the original geological conditions gradually change, making the existing layered water injection technology in some aspects unable to meet the conditions of continuous and efficient exploitation of oil and gas fields at the same time because of the injection of a large number of oil repellent water into the rock layer, coupled with the inherent groundwater. This process results in wear of oil and gas extraction equipment, passivation, rusting, and other varying degrees of wear and tear that affect the normal operation of the equipment and lead to a significant decrease in the efficiency of extraction. The traditional water injection process can achieve only a single oil drive function, and it cannot meet the needs of data collection and information monitoring, thus wasting a large amount of data and information resources. Consequently, operators cannot obtain the operating parameters of the well in time to make accurate judgments, not to mention the need to realize the refinement of water injection. The gradual development of computer technology and mobile communication technology provides more and more efficient technical methods for crude oil extraction technicians to collect more downhole data. Experts in crude oil extraction technology at home and abroad are now committed to exploring how to apply big data, artificial intelligence, mobile communication technology, and other applications to the oil and gas extraction process to realize the construction of a digital oil field. Using artificial intelligence technology, it realises an automated and integrated intelligent layered water injection system. The system carries out water injection in a refined manner through intelligent equipment, monitors the water injection situation of each oil layer downhole in real time over a long period of time, and intelligently adjusts the amount of water injected and the parameters of the equipment according to the monitoring data. This intelligent water injection system can significantly reduce cumbersome manual operations, improve the precision of water injection, and ultimately achieve the goal of improving oil recovery efficiency.

RELATED WORKS

Barreto et al. (2016) evaluated some relevant aspects of the inclusion of intelligent wells, and in a more global study of production strategy selection these researchers showed that the use of intelligent wells can significantly alter the water flow capacity and the operational design of wells . Tong et al. (2020) designed an automatic layered water injection system based on the Internet of Things. Considering that the daily injection volume of water injection wells does not meet the standard caused by the actual water injection process, Tong et al. (2020) designed an automatic injection strategy of layered water injection based on the K-means algorithm. The process advantages of the seawater treatment plant being on the seabed allows for a design that is simplified compared with a corresponding topside plant. Hegdal et al.'s (2020) study presented a fully integrated subsea sulfate removal and low salinity plant for importer of record (IOR) and exporter of record (EOR). Hegdal et al. (2020) described this system design and explained how it translates into improved reliability and availability. The ability to operate a water treatment plant on the seabed necessitates instrumentation and control that provide good condition monitoring of equipment and the ability to check and control water quality. Studying and optimizing a water injection technology scheme to meet oil field production and technology iteration are urgently needed. Chen et al. (2022) summarized the development history and status quo of oil recovery stratified water injection technology at home.

In recent years, based on a better understanding of ultra-low permeability reservoirs gradually, Changqing Oil Field formed the core technology system to enhance developing ability, such as fine water injection and fracturing.Water injection development in ultra-low permeability reservoirs in the Ordos Basin is characterised by small directional well sizes, limited water injection volumes, and conventional water injection processes. These characteristics lead to high support costs and complex manual operations, and also trigger problems such as rapid decline in zonal water injection rate. To address these challenges, Yang et al. proposed an intelligent water injection monitoring technology in 2018(Yang et al., 2018). Zhao et al. (2020) focused on oil well software metering technology, intelligent control technology of water injection wells, oil well single-pipe transportation technology, gathering and transportation, and water injection process optimization technologies. Through the research and application of the optimization and simplification technology of the surface system, the metering technology and the single-well oil collection technology were simplified, the metering station was canceled, the mixed water system was shut down, the oil and water pipe network was reduced, and the process flow was shortened. Thus, studying and optimizing a water injection technology scheme to meet oil field production and technology iteration are urgently needed. Chen et al. (2022) summarized the development history and status quo of oil recovery stratified water injection technology at home. Because of the complex and harsh oil field production environment, oil field enterprises need a set of digital intelligent monitoring systems to realize the real-time monitoring and control of oil field water injection. Xing et al. (2023) designed a field monitoring system of oil field water injection based on configuration software.

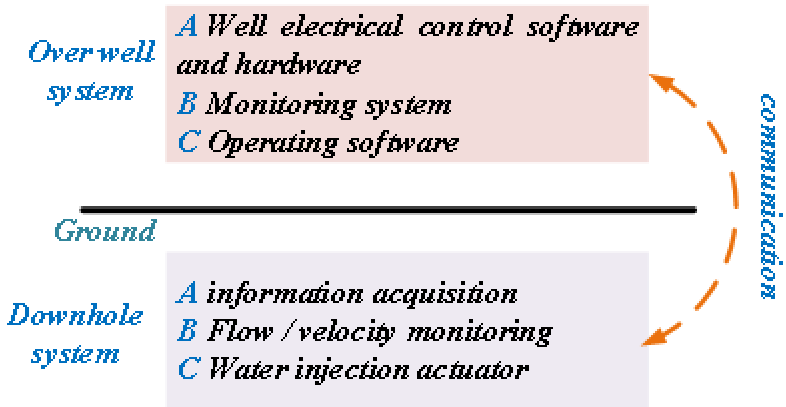
MATERIALS AND METHODS

Layered Water Injection Intelligent Control Structure

Layered water injection has been developed more maturely with the deepening of theoretical research and engineering practice. The amount and rate of water injection in each reservoir need to be determined according to the real-time working condition of the reservoir, and the parameters of temperature, pressure, and oil production need to be determined downhole (Gaixing et al., 2022). Generally, pressure and oil production are positively correlated under the ultimate pressure, and once the ultimate pressure is exceeded, the field will be transformed into low production. At the same time, changes in temperature will also have a greater impact on the yield, so to ensure the accuracy and cost-effectiveness of water injection and oil recovery, the intelligent control system needs to collect real-time downhole information to help the intelligent system determine and send out command information (Wang et al., 2019).

In fact, a variety of new sensor technologies and transportation technology to achieve engineering applications facilitate the acquisition of various types of downhole information, thereby providing favorable conditions for real-time information acquisition and detection of water injection parameters. Figure 1 shows the intelligent control structure of the layered water injection system studied in this paper. This system consists of three parts: the downhole system, the uphole control system, and the communication system. Among them, the downhole system completes the information acquisition, flow/rate monitoring, and water injection actuator; the uphole control system contains hardware and software parts of electrical control, as well as the monitoring system and operation software produced by engineers; and the communication system completes the real-time information interaction between

Figure 1. Intelligent control structure of layered water injection



the downhole system and the uphole system and often adopts the form of communication cable because the underground wireless signal will be subject to a lot of interference.

Characterization of Water Injection Flow Control Valve

The water injection flow regulating valve (RV) is the main actuator downhole, and in the internship task, the implementation of the communication cable transmission of the well control system commands regulate the water injection flow and rate to realize the automation of water injection. The RV often consists of actuators and valves, and its power type contains hydraulic, pneumatic, electric. The current RV types are electromagnetic valve, electronic, and so on. The control valve is the last link in the implementation of intelligent control decisions. The choice of a reasonable product is of great engineering significance, and therefore, some core conditions need to be considered:

- The design of the RV's spool shape and structure needs to consider the reservoir fluid characteristics and downhole imbalance.
- The smoothness of the valve and the rigidity of the material, which is due to the downhole fluid, contains friction particles and greater liquid pressure.
- The design of the RV should be structured for corrosion resistance and a wide range of temperatures, taking into account the needs of underground pressure acidification and the need for a wider temperature range.
- The design of the RV should address the need for acidification of underground pressure and the characteristics of the formation with large temperature differences.

The relative flow rate of water injection media flow through the valve and the relative openness of the relationship are known as the flow characteristics of the regulation. The ideal situation can exhibit four types of flow characteristics: straight line, parabolic, fast-opening, and logarithmic. Parabolic characteristics lie between logarithmic and straight line behaviors, while fast-opening characteristics are also found within the logarithmic and straight line control programs. Therefore, flow characteristics are often described in terms of logarithmic and straight line patterns. Linear characteristics refer to the flow behavior where the slope remains constant, indicating that the valve's linear characteristics lead to strong regulation but may also result in overshooting oscillations when the flow rate changes. When the valve is opened to a large degree, the flow rate changes are minimal, leading to weaker regulation. Therefore, it is recommended to adopt logarithmic characteristics, as they amplify the coefficient and exhibit a positive correlation with the degree of opening. This ensures better regulation capability and sensitivity across different degrees of valve opening, enhancing overall control effectiveness. The empirical method is commonly employed to select control valves, and this approach typically takes into account factors such as system quality regulation, piping technology, and load variations.

Downhole Actuator Design

The actuator works in the reservoir under high pressure water environment (about 40 megapascals [MPa]), and the actuator contains a large number of electrical equipment. Ensuring the safety and normal operation of the equipment, especially the waterproof treatment of the static state and the change of the working state, is particularly critical. Static seal is relatively simple; adhesive sealing materials to fill the configuration gap, such as general asphalt or natural rubber,, can meet this requirement. However, consider that the sealing material should have appropriate mechanical strength and hardness, high temperature does not decompose and soften the material, and the characteristics of the material's low temperature rigidity remain unchanged. The coefficient of friction and corrosion-resistant features also need to be considered. The relative difficulty of the dynamic seal is relatively large, but additional points to consider are the waterproof performance of the motor under the conditions of external action, the dynamic and static friction is quite good—that is, good elasticity, wear and tear with automatic rebound compensation, with a certain degree of self-lubricating properties.

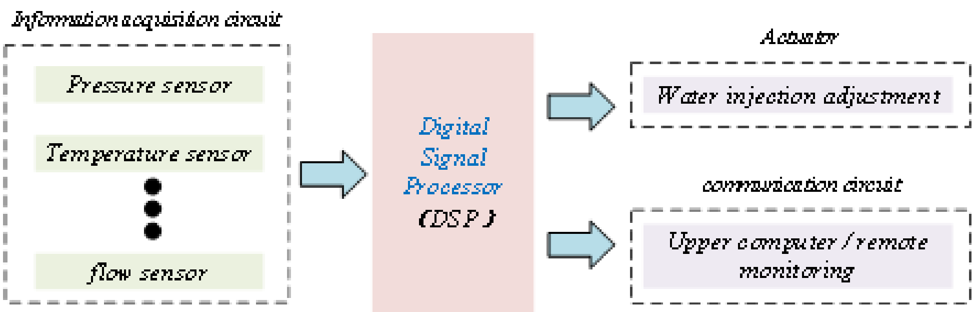
With regard to intelligent control system layered water distribution, sensors are important equipment to realize the information acquisition and downhole monitoring. The intelligent control systems often need to use flow sensors, pressure sensors, or temperature sensors. Sensor selection principles need to take into account the specific environment of the underground work, such as temperature changes and stratum pressure, because the underground fluid contains more frictional substances and minerals, easily causing interference to the sensing and thus leading to large measurement errors. Hence, the selection process should also prioritize sensors with superior anti-interference performance.

RESULT ANALYSIS AND DISCUSSION

Control System Hardware Design

The oilfield layered intelligent water injection system takes the water injection flow and flow rate at the outlet of each layered regulating valve as the main control quantity. The control concept involves utilizing a DSP, combining its hardware and software resources with peripheral circuits to achieve intelligent measurement and control within the system, and to transmit command signals. Its main components include various types of sensors based on the data, data acquisition circuits based on various types of sensors, signal output drive circuits, wired/wireless communication circuits, and other three aspects. As the core of the intelligent control system through various types of downhole and on-site sensors, DSP will be injected into the formation pressure, liquid flow rate, humidity, temperature, and so on and into electrical signals, and then through the conditioning circuit and analog-to-digital conversion (A/D) into digital signals into the DSP the process to complete the real-time acquisition of downhole conditions and feedback. On one hand, the DSP substitutes all kinds of signals into the established downhole mathematical model to obtain the optimal water injection reference instruction; on the other hand, it compares the real-time information with the reference instruction to determine whether to open the actuator for adjustment according to whether the error exceeds the preset value allowed for error. When the error signal exceeds the allowable preset value, the DSP outputs the adjustment signal and drives the adjustment mechanism through the drive circuit to realize the real-time working condition adjustment. The hardware structure of the control system is shown in Figure 2.

Figure 2. Schematic diagram of the hardware structure of the control system



The hardware design of the intelligent control system around layered water injection contains four aspects: DSP selection, information acquisition module design, communication circuit design, and anti-interference design. The DSP is the brain of the intelligent control system; throughout the system it completes all the data processing and instruction release and at the same time affects the design of peripheral circuits and product selection. Currently, there are more DSP products available on the market to fulfill this requirement, including Texas Instruments DSP, STMicroelectronics stm32, Xilinx production of editable logic arrays (Field Programmable Gate Array [FPGA]), and microcontrollers. DSP has become the first choice for industrial DSP scenarios owing to its strong anti-interference, 150-MHz main frequency, and 32-bit floating point operation. The information acquisition module needs to complete the amplitude change of the sampled electrical signals and analog-to-digital conversion, but because the DSP has its own 12-bit AD converter module, the information acquisition module needs to convert the electrical signals only into 0~3V electrical signals, which can be directly sent to the AD interface of the DSP. If the sampled signals are AC information, it is necessary to implement the corresponding voltage boost and then internally eliminate this boosted voltage in the DSP.

The communication circuit is responsible for completing the serial programming and online debugging of the DSP chip, realizing the remote observation of data and sending commands through the industrial computer, and providing basic data for the visualization of downhole working conditions. The communication design selects wireless or wired communication according to the needs. The underground working environment is relatively harsh, and the sampling data will often be subject to a variety of interference, including the internal electrical design of the system or external electromagnetic interference, that will cause greater interference to the data acquisition and transmission, thus distorting the signal. Therefore, the following measures are needed to eliminate electromagnetic interference:

- Use two-wire balanced transmission to eliminate serial mode interference
- Use floating technology to eliminate the common-mode interference
- Increase the distance between the transmission line and strong and weak power
- Separate design

Based on TMS320F28335 Software Design

Software is the core of the DSP operation, and the research in this paper on layered intelligent water injection system to be used in Texas Instruments production of TMS320F28335 for the computing chip. The chip has a fast speed, general-purpose IO ports (88), and the main frequency of up to 150 MHz 12-bit 16-channel ADC can reduce the peripheral sampling circuit mode conversion design. The chip is compatible with the fixed point of the C28x controller and is well-suited for industrial scenarios.

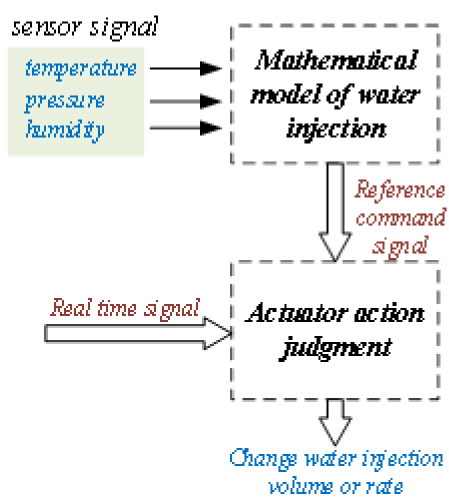
It is also compatible with the fixed-point C28x controller, which has better applicability in industrial scenarios.

Table 2. TMS320F28335 resource table

Resource name	Parameters	Resource name	Parameters
CPU	TI TMS320F28335 floating point DSP	Core link board	2×80 pin pin header
ROM	Inner 256K × 16 bit	JTAG	Debug
RAM	Infrared 34K × 16 bit	DAC	1 x DAC 0~5V
EEPROMR	2 kbit	ADC	1 x 16 channel ADC

Figure 3 shows the software flow block diagram based on the TMS320F28335 that we developed for this paper. To facilitate software writing, debugging, and later maintenance, we designed software using modular ideas and divided the realization of different functional procedures into module function development. Unified definition of the interface information was necessary to facilitate the overall debugging and complete the various modules. After debugging was satisfactory, the modules were then accessed one by one to the main program to ultimately achieve the overall software design. The information acquisition program contains temperature, humidity, pressure, flow, and other information, but we also designed the program according to other needs to increase the different sensors, during data acquisition, the system accepts cyclic interrupt information and accesses the calculation subroutine. It reads multiple sets of sampled data, filters out larger error values, and obtains accurate values through arithmetic averaging and sampling cycle. This process enables the system to perform pressure operations and store the results effectively. After obtaining the pressure value, we reset and initiate the program to prepare for the next cycle of data reception.. The control program substitutes the data obtained from the sampling program into the established water injection model to get the reference command signal for water injection in each layer under the working condition. This program then seeks the error between the actual sampling signal and the command signal and then obtains the modulation signal of this control cycle after the compensation operation. This step drives the equipment to function and thereby concludes the comprehensive intelligent process of acquiring information, processing information, and completing actions.

Figure 3. Flowchart of TMS320F28335-Based software design



Research on Adaptive PSO Algorithm

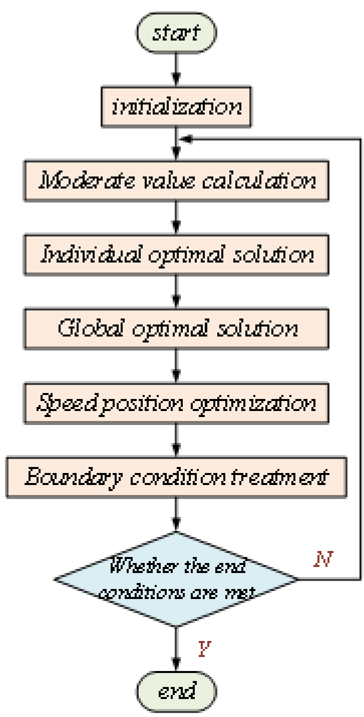
The core of the intelligent control system is to automatically and accurately adjust the water injection rate of each reservoir according to the real-time conditions of the well. To achieve this control goal, the influencing factors of the water injection system need to be considered to determine the structure of the reservoir downhole, while at the same time the economic aspects of water injection also need to be considered. Thus, only the control system is essentially a multiobjective optimization problem. To fully realize the common balance of multiple objectives, establishing a mathematical model with economic optimization as the objective function is necessary, and the balance of water supply and injection, pressure balance at the injection point, maximum oil production, water injection cost, and other factors also must be considered.

For this kind of multiparameter, multiobjective optimization problems, solving the algorithm with better convergence speed and global search ability is necessary. The PSO algorithm offers these advantages. By constantly comparing the fitness values, PSO enables the control system to experience the best position comparison by constantly iterating the new individual optimal value and the global optimal value. PSO produces new particles for boundary condition detection, and if it meets the minimum error or the maximum number of loops, then exit the program. If it does not meet these conditions, the search continues. Adaptive PSO is based on the existing particle algorithm. It draws on the idea of mutation, re-initializing certain variables with a certain probability to continuously reduce the search space in the search process and adjust to the original search for the optimal position. Its process structure is shown in Figure 4.

Field Application

Taking a water injection well as an example, we adopted the method of three-stage water injection. Note that in this method all the water injectors in the well are in the open state, and the layered

Figure 4. Flow chart of adaptive PSO algorithm



water injection is carried out within 2 days. The injection is then measured and allocated by layers. The highest temperature in the well is 110 degrees, and the water injection pressure is 17 MPa. The well adopts a 120-degree water distributor. After the intelligent water injection system completes the measurement and adjustment, it turns to the water injection state, and the remote- control computer displays the operation parameters of water injection wells on the interface, thus obtaining the data of water injection opening, downhole temperature, injection pressure, and cumulative flow rate of each formation. The surface water injection pressure is 6.6 MPa, and the daily water injection volume is 202 cubic meters. After 48 hours of combined injection, the intelligent water injection system calculates the water absorption index by sections, and data information, such as water injection pressure, can be obtained from the display interface. Combined with the water injection absorption of each formation and the maximum injection pressure, the system designs the first section to be injected with 25 cubic meters per day, the second section is set for 40 cubic meters per day, and the third section is set for 35 cubic meters per day. The total injection volume per day reaches 100 cubic meters, and the injection pressure is designed to be 9 MPa. After the injection allocation reaches a steady state, the control command is sent from the ground control system to read the pre-and post-pressure of each formation nozzle and the actual injection allocation, and the injection allocation rates for the three sections reach 99%, 99%, and 100%, respectively.

CONCLUSION

In this paper we took oil field layered water injection as the engineering background, combined digitization and information technology, and designed the oil field layered water injection intelligent control system. First, we explained that the stratified water injection system is a new trend in line with the future development direction of the oil field, summarized its advantages and domestic and international theoretical research and engineering practice cases, provided the overall structure of the oil field stratified water injection intelligent control system, and completed the study of downhole equipment, such as flow regulating valves and high-pressure seals, based on the structure. We then completed the design of hardware peripheral circuits and modular software process design based on the TMS320F28335 chip and finally examined a multiparameter, multiobjective intelligent control system based on the adaptive PSO algorithm. Immediately afterward, we completed the hardware peripheral circuit design and modularized software process design based on the TMS320F28335 chip. We then studied the multiparameter, multiobjective optimization intelligent algorithm based on the adaptive PSO algorithm.

Oil field layered water injection is an important way to enhance the growth of oil fields. The rapid development and engineering applications of DSP, sensor technology, communication technology, and digital technology, among others, have made the study of its intelligent control system more popular, and engineering applications are just around the corner. In this paper, we focused on only the structure of the intelligent system and hardware and software components of the theoretical exploration and feasibility study. The next step will be to combine the structure and components with the system in different reservoir conditions to carry out processes that are more in line with the engineering characteristics of the research to help the construction of an intelligent oil field.

The design of an intelligent control system for layered water injection in oil fields is a challenging research task that needs to overcome the limitations of data acquisition and processing, model and algorithm selection, implementation and application, and economic and environmental factors. Future research needs to optimize data acquisition and analysis, improve the adaptability of models and algorithms, strengthen the safety management of system implementation and application, comprehensively consider the economic and environmental impacts, and conduct multidisciplinary cross-research to further improve the scientific and practical aspects of system design.

DATA AVAILABILITY

The figures and tables used to support the findings of this study are included in the article.

CONFLICTS OF INTEREST

We declare that we have no conflicts of interest.

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